



Attentional modulation of neural sound tracking in children with and without dyslexia

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Abstract

Auditory selective attention forms an important foundation of children's learning by enabling the prioritisation and encoding of relevant stimuli. It may also influence reading development, which relies on metalinguistic skills including the awareness of the sound structure of spoken language. Reports of attentional impairments and speech perception difficulties in noisy environments in dyslexic readers are also suggestive of the putative contribution of auditory attention to reading development. To date, it is unclear whether non-speech selective attention and its underlying neural mechanisms are impaired in children with dyslexia and to which extent these deficits relate to individual reading and speech perception abilities in suboptimal listening conditions. In this EEG study, we assessed non-speech sustained auditory selective attention in 106 7-to-12-year-old children with and without dyslexia. Children attended to one of two tone streams, detecting occasional sequence repeats in the attended stream, and performed a speech-in-speech perception task. Results show that when children directed their attention to one stream, inter-trial-phase-coherence at the attended rate increased in fronto-central sites; this, in turn, was associated with better target detection. Behavioural and neural indices of attention did not systematically differ as a function of dyslexia diagnosis. However, behavioural indices of attention did explain individual differences in reading fluency and speech-in-speech perception abilities: both these skills were impaired in dyslexic readers. Taken together, our results show that children with dyslexia do not show group-level auditory attention deficits but these deficits may represent a risk for developing reading impairments and problems with speech perception in complex acoustic environments.

KEYWORDS

auditory attention, dyslexia, EEG, reading, speech perception

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Research Highlights

- Non-speech sustained auditory selective attention modulates EEG phase coherence in children with/without dyslexia
- Children with dyslexia show difficulties in speech-in-speech perception
- Attention relates to dyslexic readers' speech-in-speech perception and reading skills
- Dyslexia diagnosis is not linked to behavioural/EEG indices of auditory attention

1 | INTRODUCTION

Much of our daily life relies on successful auditory attention, whether we are trying to listen to our boss in a meeting while children enjoy the nearby playground, or when a child listens to their online school teacher while their younger brother watches a cartoon on TV next door. Such situations often force us to single out a sound stream from a complex mixture of sounds and maintain focus on the target over time to extract and make use of relevant information. Selective attention allows us to filter out unimportant sounds while facilitating the encoding of relevant information: it is thus vital for learning (Posner & Rothbart, 2005; Stevens & Bavelier, 2012). In particular, the development of the auditory attention system is thought to shape the way language is acquired and processed, starting very early in development (de Diego-Balaguer et al., 2016; Gomes et al., 2007; Myachykov & Posner, 2005).

Later in development, auditory attention may be particularly relevant for reading acquisition, which requires awareness of the sound structure and discrete units of the continuous speech signal (e.g., Goswami, 2011). This ability typically relies on explicit verbal instructions. Thus, on a global level, inattention may prevent children from benefiting from reading-related activities in the classroom, and predispose them to early reading acquisition difficulties (Dally, 2006; Dittman, 2013; Sims & Lonigan, 2013). Less effective attentional mechanisms may hinder directly the development of crucial cognitive skills associated with reading acquisition, such as phonemic awareness and the acquisition of sub-lexical spelling-sound mappings (Dally, 2006; Martinussen et al., 2014; Plourde et al., 2018; ten Braak et al., 2018; van de Sande et al., 2013), processes that rely upon consistent categorization of the speech units (Boets et al., 2008; Vandermosten et al., 2010). Auditory selective attention may facilitate such phonetic categorisation learning by biasing perception towards the most informative acoustic cues for each phonemic category, thus enhancing the perceived differences between categories (Francis et al., 2008; Francis & Nusbaum, 2002; Gordon et al., 1993). In addition, directing attention to the most informative acoustic dimensions provides a strategy to cope with talker- and context-dependent variability, such as the presence of background noise in the environment (Heald & Nusbaum, 2014; Holt et al., 2018). Finally, attentional mechanisms may play a role in developing automaticity in reading (Laberge & Samuels, 1974), for example, by facilitating access to phonological information from print (Reynolds

& Besner, 2006). Therefore, impaired attention mechanisms or skills could significantly affect processes underlying reading development, and thus may make it difficult for children to become fluent readers (Shaywitz & Shaywitz, 2008).

Links between auditory attention, language, and reading processes may have particular implications for developmental dyslexia (hereafter, dyslexia). As defined by the American Psychiatric Association (2013), dyslexia is a specific learning disorder characterised by persistent problems with accurate and fluent word reading and spelling. Deficits in various aspects of phonological processing are often observed in children and adults with dyslexia (Goswami, 2000; Ramus & Szenkovits, 2008). Traditionally, weak phonological representations have been seen as the core causal factor underlying the disorder (e.g., Vellutino et al., 2004). Over the years, alternative theoretical accounts of dyslexia have focused on a range of other deficits, including—but not limited to—deficits in letter-speech sound integration (Blomert, 2011), auditory temporal processing (Tallal, 1980, 2004; Vandermosten et al., 2010, 2011), and visual or auditory attention (Bosse et al., 2007; Hari & Renvall, 2001). The heterogeneity of symptoms found in dyslexic readers (e.g., Heim et al., 2008; Menghini et al., 2010; Willems et al., 2016) has recently prompted a shift towards a multiple deficit view, with reading problems resulting from individually variable combinations of language-specific and domain-general deficits (Pennington, 2006; Peterson & Pennington, 2015; Van Bergen et al., 2014). A theoretical framework moving beyond the identification of a single core deficit also accounts for the high comorbidity among developmental disorders (Pennington, 2006). Indeed, up to 40% of individuals with dyslexia also receive a diagnosis of attention deficit and hyperactivity disorder (ADHD) and vice-versa (Germanò et al., 2010; Willcutt & Pennington, 2000), with stronger association of reading disorders with inattention than with the hyperactivity-impulsivity symptoms of ADHD (Greven et al., 2011; Hendren et al., 2018; Plourde et al., 2015).

Among the aforementioned heterogeneous deficits, attentional problems outside of language have often been reported in dyslexic readers without a co-occurrent formal diagnosis of ADHD. For instance, groups of participants with dyslexia have shown poorer stimulus-driven engagement of attention in both auditory (Facoetti et al., 2003, 2005, 2010) and visual modalities (Facoetti et al., 2005, 2003, 2010; Ruffino et al., 2010, 2014). Similar trends have been seen in amodal attentional shifting (Facoetti et al., 2008; Lallier et al., 2009, 2010, 2013). Some of these studies have also shown reduced



P3 ERP responses to rapidly presented non-speech visual and auditory stimuli (Lallier et al., 2010). Although more limited, there have also been reports of poorer ability in top-down control of attention, for example, in sustaining auditory attention (Menghini et al., 2010) and in suppressing irrelevant or distracting information in both visual (Roach & Hogben, 2007, 2008) and auditory domains (Gabay et al., 2020).

Further indications of putative top-down auditory attentional deficits in dyslexia are found in studies reporting challenges in perceiving speech in adverse listening conditions. Speech perception difficulties in children with dyslexia have been shown under a wide range of distracting or masking conditions, including speech-shaped noise as well as babble noise (Chandrasekaran et al., 2009; Dole et al., 2012; Nittrouer et al., 2018; Ziegler et al., 2009). When speech perception was assessed both under silent and in noisy conditions, individuals with dyslexia showed more consistent deficits when distracting speech or noise is presented (Calcus et al., 2015, 2016, 2017; Ziegler et al., 2009, Ziegler et al., 2005; for a review, see Calcus et al., 2018). Thus, noise may reduce the availability of disambiguating acoustic cues, making it difficult for dyslexic listeners to compensate for their weak or unspecified speech sound representations (Ziegler et al., 2009). In turn, given that everyday listening conditions are rarely pristine, such difficulties with speech-in-noise perception may hamper the acquisition of precise phonological representations prior to and during reading acquisition (e.g., Calcus et al., 2017; Poelmans et al., 2011), suggesting a bidirectional interaction between difficulties in perceiving speech in noisy everyday environments and phonological impairments (Boets et al., 2011; Ziegler et al., 2009).

When competing sound sources are at play, sensory processing relies considerably on selective attention (Shinn-Cunningham, 2017). Indeed, speech-in-noise perception was shown to draw upon top-down attention in other developmental and adult populations (e.g., Oberfeld & Klöckner-Nowotny, 2016; Tierney et al., 2020). Turning to speech perception difficulties in dyslexic readers, it is therefore possible that poorer selective attention exacerbates dyslexic readers' speech perception difficulties when listening conditions are unfavourable (Calcus et al., 2016, 2017, 2018; Hazan et al., 2009; Messaoud-Galusi et al., 2011; Ziegler et al., 2009). Individual differences in auditory attention may also explain the considerable variability in speech-in-noise performance in dyslexic readers (Calcus et al., 2017; Messaoud-Galusi et al., 2011), paralleling the heterogeneity of dyslexic readers' auditory processing profiles (Lallier et al., 2013). To our knowledge, in dyslexic readers, links between auditory attention and difficulties with perceiving speech in distracting conditions have yet to be examined, possibly due to the lack of methodological tools for assessing auditory attention skills most relevant to the demands of complex acoustic environments (Calcus et al., 2018).

A different theoretical account of speech perception deficits in dyslexic readers suggests that they stem from a failure in extracting relevant acoustic cues in speech streams, such as amplitude modulation and transient acoustic cues (Goswami, 2011; Leong et al., 2011; Poelmans et al., 2011; Power et al., 2016). Such a process necessarily

becomes more challenging in noise (e.g., Boets et al., 2011; Poelmans et al., 2011; Van Hirtum et al., 2019; Van Hirtum et al., 2021). Relatedly, dyslexic readers' poorer tracking of the temporal structure of speech has been linked to atypical low-frequency neural entrainment, that is, the alignment of the timing of neural activity with the temporal regularities of an exogenous stimulus (Goswami, 2011; 2019; but cf Lizarazu et al., 2021). This lack of temporal alignment is postulated to lead to processing deficits at the prosodic and syllable levels (Goswami, 2011, 2015, 2019) with subsequent direct (Di Liberto et al., 2015, 2018) or indirect (Goswami et al., 2011; Goswami, 2019) effects on phonemic processing.

More generally, tracking the temporal envelope of speech via phase alignment of low-frequency neuronal activity has been proposed to be crucial for speech decoding and intelligibility (e.g., Luo & Poppel, 2007). In noisy or multi-talker auditory scenes, neural entrainment could serve as a critical mechanism of auditory selection, that is, to preferentially track relevant continuous speech at the expense of concurrent distractors (Ding & Simon, 2012; Hambrook & Tata, 2014; Horton & Srinivasan, 2013; Kerlin et al., 2010; Zion Golumbic et al., 2013). In a first study, Lakatos and colleagues introduced the notion of entrainment as a putative mechanism for selective temporal attention. Here non-human primates were presented with quasi-rhythmic streams of visual and auditory stimuli in antiphase (Lakatos et al., 2008). When attending to one of the two streams, delta oscillations in primary visual and auditory areas became entrained to the attended modality, such that maximal excitability corresponded with expected events in the attended stimulus stream, and oscillations were in opposite phase in the two attention conditions.

In humans, prior electrophysiological studies showed that directing attention to the temporal structure of auditory stimuli modulates phase tracking and coherence specifically at the frequency of the attended stimuli in adults (Besle et al., 2011; Henry & Obleser, 2012; Laffere, Dick, & Tierney, 2020) and in 11-year-old children (Laffere, Dick, Holt, et al., 2020). Moreover, selective phase coherence/alignment was associated with greater stimulus detection performance in sound-feature detection paradigms (Henry & Obleser, 2012; Laffere, Dick, Holt, et al., 2020; Laffere, Dick, & Tierney, 2020). Furthermore, cortical tracking of attended speech via phase alignment to its temporal envelope was shown to be more robust than of concurrent unattended speech, indicating that selective attention modulates speech processing (Ding & Simon, 2014; Kerlin et al., 2010; Vander Ghinst et al., 2016; Zion Golumbic et al., 2012; Zion-Golumbic et al., 2013).

Finally, studies with transcranial alternating current stimulation showed that manipulating neural entrainment can facilitate perception of speech in competing speech (Riecke et al., 2018; Zoefel, Archer-Boyd, & Davis, 2018), demonstrating that neural entrainment plays a causal role in speech-in-speech processing. Taken together, those findings provided evidence for the hypothesis that selective attention can modulate neural entrainment (i.e., selective entrainment; Obleser & Kayser, 2019) and that selective entrainment could be key in adverse listening conditions.



1.1 | The current study

Phonological processes may rely upon the ability to direct attention to relevant speech cues while suppressing other salient features in order to segment and manipulate sound segments. Deficits in auditory attention may thus affect phonological awareness development, and in turn, reading acquisition. In dyslexic readers, evidence showing non-speech attentional deficits and difficulties in perceiving speech in adverse listening conditions also suggest a putative contribution of attention to reading development. More specifically, the observation that dyslexic readers' speech perception deficits are more consistently found when concurrent noise is present suggests that top-down selective auditory attention deficits could exacerbate their phonological and speech perception difficulties. To date, it is unclear whether non-speech selective attention and its underlying neural mechanisms are impaired in children with dyslexia and to which extent these deficits relate to individual reading and speech perception abilities in suboptimal listening conditions.

In the present EEG study, we assessed sustained auditory selective attention skills and neural (EEG) correlates in 7-to-12-year-old children with and without dyslexia using a task requiring participants to direct attention to one of two rhythmic tone-streams. The tone-streams were presented in antiphase at 3 Hz. Within the attended stream, children were asked to identify occasional tone sequence repeats while ignoring the competing tone-stream. A non-speech attention task was deliberately chosen to minimise potentially confounding language and phonological difficulties of children with dyslexia, and thus, to be able to examine whether and to what extent poor speech perception abilities are due to variability in selective attention to continuous sounds. At the same time, this task assesses attentional demands that are characteristic of complex naturalistic environments: participants must direct and maintain attention to a target stream over time, integrate information within the attended stream, and simultaneously suppress attention to a distractor stream.

Based on previous findings showing that selective neural entrainment benefits attentional selection to continuous sound (Besle et al., 2011; Henry & Obleser, 2012; Laffere, Dick, Holt, et al., 2020; Laffere, Dick, & Tierney, 2020; Laffere, Dick, Holt, et al., 2020), here we hypothesised that sustained selective attention to one of two tone streams would be linked to increased phase coherence at the attended frequency (3 Hz). To do so, phase coherence at 3 Hz during the active conditions (i.e., when attention was selectively directed and sustained towards one of the two tone streams) was compared to that when they were passively listening to similar stimuli. Time-frequency neural metrics were used because they are suitable to examine neural tracking of continuous and fast paced sound; the 6 Hz tone presentation rate does not permit measurement of tone-evoked event-related potentials as their responses overlap in time. We also examined potential effects of attention on total power at the attended frequency, to ensure that putative attentionally-modulated changes in phase coherence did not reflect changes in overall strength of neural activity at the attended frequency or in signal-to-noise ratio across conditions. Furthermore, we

contrasted phase coherence and total power at the overall (dual-band) sound presentation frequency (6 Hz). This allowed us to disentangle neural effects of sustained selective attention from those related to overall (exogenous) attention to the auditory signal as a whole. Motivated by the EEG literature on attentional processes (Klimesch, 2012) as well as reading difficulties (Babiloni et al., 2012), we also analysed power in the alpha band (8–12 Hz).

To test hypotheses about the relationship of sustained auditory selective attention to reading, speech perception and phonological impairments, we first compared behavioural and EEG metrics of sustained auditory selective attention in children with and without dyslexia. Second, we examined whether children with dyslexia showed impaired speech-in-speech perception abilities, and whether behavioural and EEG metrics of sustained auditory selective attention predict individual differences in speech-in-speech perception, reading fluency and phonological abilities, across and within the two groups of dyslexic and typical readers.

2 | MATERIALS AND METHOD

2.1 | Participants

106 7-to-12-year-old children (59 with dyslexia and 47 typically developing) were recruited for the study. All were native Dutch speakers. Children's ethnicity was White ($N = 102$), African American ($N = 3$) and Asian ($N = 1$). Children with dyslexia were recruited from the Regional Institute for Dyslexia (RID) and were on a waiting list for treatment. Dyslexia diagnosis was provided by the RID based on the results of cognitive psycho-diagnostic testing and standardized reading measures, including the 3DM test battery (Differential Dyslexia Diagnosis; Blomert & Vaessen, 2009) and the Wechsler Intelligence Scale for Children (WISC). Children with dyslexia scored at or below the 10th percentile on standardised reading measures. Data from two children were excluded due to hearing impairments; additional data from one participant was excluded due to having completed a treatment for dyslexia in another institution. None of the children with dyslexia were diagnosed with ADHD. One child with a co-occurring diagnosis of Asperger's syndrome was included in the final sample. Typically developing children were siblings or acquaintances of the participants with dyslexia or were recruited via word of mouth. Parents were asked to report any neurodevelopmental disorder diagnosis and also whether the child had relatives with a diagnosis of dyslexia. None of the children were diagnosed with dyslexia, ADHD or other neurodevelopmental disorders. Group comparisons of reading(-related) skills of children in the typical readers group with and without dyslexia hereditary risk (as indexed by having a relative diagnosed with dyslexia) were performed and no significant differences were found ($p > 0.05$). Parents gave written informed consent for participation, and children received a small gift and a certificate as a reward for participating. The study was approved by the ethics committee of the Faculty of Psychology and Neuroscience, Maastricht University.

TABLE 1 Participants' characteristics, reading and reading-related skills of children with and without dyslexia.

Sex (m/f)	Dyslexic readers (N = 51)			Typical readers (N = 38)			Dyslexic vs typical readers	
	Ratio			Ratio			x(df) ^a	p
	Mean	SD	Range	Mean	SD	Range	t(df) ^b	p
	29/22			24/14			0.358(1)	0.549
Age (years)	9.57	1.16	7.67-12.42	9.62	1.25	7.33-12.33	-0.192(87)	0.849
Verbal IQ (Vocabulary)	11.24	2.53	6-17	11.84	2.57	6-19	-1.11(87)	0.270
Non-verbal IQ (Block design)	9.80	2.95	3-19	10.50	3.13	5-17	-1.073(87)	0.286
EMT (Standardized)	2.96	2.41	1-10	9.05	3.31	2-19	-10.052(87)	<0.0001
EMT (Raw)	30.92	13.25	5-65	56.84	16.92	20-102	-8.108(87)	<0.0001
3DM Word Fluency (T)	29.25	6.13	20-41	49.97	10.24	34-75	-11.079(56.38)	<0.0001
3DM Word Fluency (Raw)	61.57	26.79	2-112	113.16	29.56	23-166	-8.597(87)	<0.0001
3DM Word accuracy (T)	32.86	11.50	20-55	51.25	9.47	23-61	-8.031(87)	<0.0001
	N = 51			N = 34 ^c				
Phonological awareness (T)	37.76	8.14	21-54	48.06	10.29	27-67	-5.134(84)	<0.0001
RAN—Letters (T)	34.37	7.79	20-51	45.44	10.92	24-71	-5.106(55.016)	<0.0001
RAN—Digits (T)	36.69	7.88	20-52	45.59	10.09	28-68	-4.556 (84)	<0.0005

Abbreviations: EMT, One-Minute-Test (word reading fluency); RAN, rapid automatized naming.

^aChi-squared test.

^bIndependent sample t-test.

^cData from four participants went lost due to software issues.

Of the 103 participants, five did not complete all three conditions of the sustained auditory selective attention task due to lack of compliance (see Electrophysiological Testing section). Of the remaining 98 participants, six additional participants were excluded due to technical problems in saving the triggers; three more participants were excluded because of noise sourcing from adjacent electrodes which impeded signal replacement using the neighbouring electrodes' weighted average interpolation technique (ft_channelrepair.m from Fieldtrip; see EEG Recording and Data Processing).

After these exclusions, data from 89 participants remained. Participants' age, IQ, reading, and reading-related skills are reported in Table 1. Data from the 3DM battery test of four participants were not saved due to software issues and two participants were not administered the One-Minute-Test (EMT; Brus & Voeten, 1973) for reading fluency due to time constraints (see Reading and Reading-Related Skills section). Multiple imputation in SPSS (version 26.0, IBM Corp., Armonk, NY), with EMT scores functioning as a predictor, was used to replace the four missing 3DM reading scores. Reading scores from the 3DM reading task were then used in the analyses as a measure of reading fluency.

2.2 | Overview of the procedure

The children underwent electrophysiological and behavioural testing. The two sessions lasted around 1 h and 45 min each. The order of both sessions was randomised over participants, so that half of the participants of each group (dyslexic and typical readers) started with behavioural testing, and the other half of each group started with EEG

testing. Children took short breaks between tasks and a longer break (30/40 min) between the behavioural and electrophysiological sessions. Behavioural and EEG testing occurred in two rooms in a silent area within the RID.

2.3 | Electrophysiological testing

2.3.1 | Sustained auditory selective attention task

Stimuli

In this experiment, participants listened to two pure tone streams, one higher-frequency stream and the other lower (see Figure 1 for schematic and SI for stimulus examples). The low- and high-frequency-band streams were created by stringing together series of three-tone mini-sequences (generated in Matlab at 44.1 kHz sampling rate). Each mini-sequence was generated by randomly choosing three tone frequencies from the 'tone pool' for each stream: low-frequency-stream tones could be 370 Hz (F#4), 415.3 Hz (G#4) or 466.2 Hz (A#4), while high-frequency-band tones could be 740 Hz (F#5), 830.7 Hz (G#5) and 932.5 Hz (A#5). Each tone was 166.67 ms long, and always followed by 166.67 ms silence (like a musical 'rest'). When strung together, each three-note mini-sequence was followed by a 333.33 ms silence.

Importantly, as shown in Figure 1, the low- and high-frequency-band streams were temporally interleaved, such that the participant heard low-high-low-high-low-high tones, followed by a silent period the same length of two tones. This series of six interleaved tones followed by a silence was considered a trial.

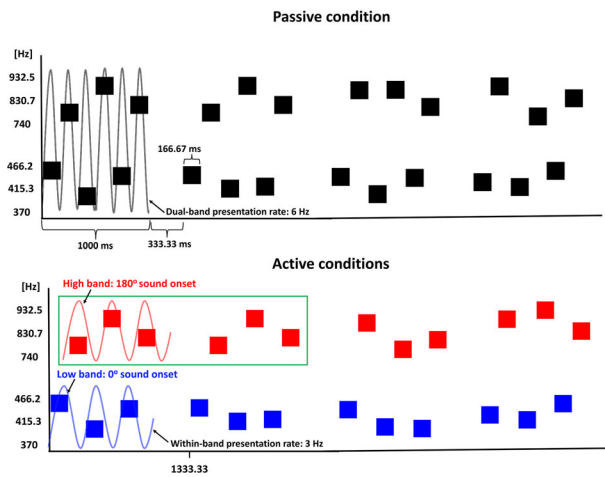


FIGURE 1 Schematic of the sustained auditory selective attention task. The target and distractor tone streams were presented simultaneously in antiphase. Each block represents a 166.67 ms sine wave tone. The within-band presentation rate was 3 Hz (one note every 333 ms), but the dual-band presentation rate was 6 Hz (one note every 166.67 ms). Tone sequences began every 1333.33 ms. During the active conditions, participants were asked to detect repetitions of sequences of three tones, such as the one in the green square. These repetitions occurred five times within each block of 30 three-tone sequences.

Thus, the rate of tone presentation *within* each frequency band was 3 Hz (one tone every 333 ms) while the rate of tone presentation *collapsing across* frequency bands was 6 Hz (one tone every 166.67 ms). The stimuli are perceived as two isochronous, temporally interleaved and spectrally distinct melodies.

Based on in-lab piloting, tones in the high-frequency band were presented at 40% of the amplitude of lower-frequency tones to ensure that the perceived loudness of the two bands was approximately balanced. Both the high- and low-frequency band were presented binaurally, in order to avoid a stream selection strategy based on spatial cues.

Task

During the task, children were sitting in front of an Iiyama 21.5' computer monitor. ER-3C insert earphones (Etymotic Research, Elk Grove Village, IL) were used for sound presentation at 72–73 dB SPL, as measured using a RION NA-27 Sound Level Meter with an NH-20 microphone. The experiment consisted of three conditions of ten blocks each. In the first condition, participants were asked to attend to the high band, in the second condition, to attend to the low band, and in the third and final condition, to passively listen to the stimuli. This order was fixed across all subjects to minimise cross-subject variability due to condition order, given that a primary goal was to investigate individual differences.

Each block contained 30 trials and was 41s long; there were 300 trials per condition. During the active conditions, participants were asked to detect and report within-attended-band sequence repeats via a Cedrus RB-844 response box. In each block there were five

repeated sequences in each band; the timing of repeats was quasi-random (repeated sequences were always separated by at least one non-repeated sequence). Participants were asked to ignore the distracting band and the sequence repeats within it; across blocks, there were equivalent numbers of repeats in both bands. A repeat was recorded as being correctly detected if the participant provided a response between 333 ms before and 1670 ms after the end of the last tone in a repeated sequence. Correct target detection began before the end of a stimulus because a repeat could potentially be detected as soon as the final tone of a sequence started.

To ensure children's engagement, the EEG task and instructions were gamified. Participants saw a spaceship at the centre of the screen with moving dots in the background mimicking a space environment. They were told that the sounds were produced by the ship's radar and that they needed to listen to them to detect asteroids which were approaching from above (attend high band) or from below the spaceship (attend low band). An approaching asteroid was signalled by the repeated sequences; to avoid it, they had to press the button. Feedback for correct and incorrect responses was given at the centre of the screen (Dutch: 'Raak/Fout'; English: 'Hit/Wrong') along with a score on the top right corner of the screen. Players received an increase of 20 points for each identified target, a decrease of 2 points for each missed target and a decrease of 5 points for each false alarm.

Before the task, children underwent a short practice with the experimenter to familiarise themselves with the stimuli. This session included a block of attending to single-stream stimuli and identifying related targets, along with practice blocks with dual-stream stimuli for each active condition (attend-high and attend-low). The stimuli were played over a speaker and participants were asked to tap on the table every time they heard a target. The experimenter subsequently gave them feedback regarding their performance to ensure that the task was understood. The children moved onto the task once they were able to identify at least 3/5 targets within the last block.

EEG recording and data processing

Electrophysiological data were recorded from a 64-channel actiCHamp system (Brain Products). EEG data were recorded with a sampling rate of 25000 Hz and referenced online to FCz. Offline re-referencing was not carried out. A ground electrode was located on the forehead. Impedance was kept below 20 k Ω . To achieve precise temporal synchronisation between stimulus presentation and triggering signal, an RTBox was used for detecting stimulus onsets and sending trigger pulses to the EEG data acquisition laptop (Li et al., 2010). Stimulus onsets and trigger pulse events were then referenced to the same system clock.

Pre-processing was carried out with MATLAB (Mathworks) based customised scripts including Fieldtrip (Oostenveld, Fries, Maris, & Schoffelen, 2011) and EEGLAB (Delorme & Makeig, 2004). Independent Component Analysis (ICA) was performed to remove ocular artefacts, identified by visual inspection of the topography and the time course of the components. EEG data were then downsampled to 500 Hz and a high-pass Butterworth filter at 1 Hz and a low-pass filter of 30 Hz were applied. Electrodes showing noise across the experiment



were interpolated using the neighbours weighted average technique (ft_channelrepair.m from Fieldtrip; applied to three participants).

Following previous in-lab studies that characterised attention-driven neural entrainment (Laffere, Dick, & Tierney, 2020; Laffere, Dick, Holt, et al., 2020), we extracted inter-trial phase coherence (ITPC) at the attended-band presentation rate (3 Hz) and at the overall stimulus presentation rate (6 Hz). We also extracted total power at the same frequencies as an additional neural metric of cortical tracking. Note that total power includes both phase-locked and non-phase-locked power, and thus, it is a partially orthogonal neural measure to ITPC.

Prior to calculation of ITPC, EEG data were segmented into 1.333 s epochs, time-locked to the stimulus onset. Epochs with voltage exceeding $\pm 125 \mu\text{V}$ were automatically marked for rejection. On average, 94.4% of trials were kept for analysis, with no significant difference between conditions for participants with dyslexia (attend-high: mean 285.37 trials [SD = 14.78, range = 232–299]; attend-low: 284.66 trials [SD = 13.97, range: 247–299]; passive: 277.21 trials [SD = 22.11, range = 200–299]) and without dyslexia (attend-high: mean 286.34 trials [SD = 14.77, range: 238–299]; attend-low: 284.74 trials [SD = 22.29, range = 209–299]; passive: 281.46 trials [SD = 18.17, range = 231–299]). No analyses were performed based on task performance, due to the limited number of trials in which targets occurred (50 targets per condition). A Hann-windowed Fast Fourier Transform (FFT) was first applied to each 1.333 s epoch. Then, at each frequency, the complex vector was converted to unit length to retain the phase component while discarding amplitude. Unit vectors were then averaged, with ITPC defined as the length of the resulting averaged vector. ITPC ranges from 0 to 1, with 0 indicating no phase alignment across trials, and 1 indicating perfect phase alignment across trials.

For analysis of total power, EEG data were segmented into 40-second epochs, time-locked to stimulus onset; epoch duration is equivalent to one block of stimuli (30 tone-sequences). Each epoch was transformed into the frequency domain using a FFT. The resulting frequency spectrum was then averaged across epochs for each condition.

Processed data for which parents have given (anonymised) data sharing consent are available on reasonable request.

2.4 | Behavioural testing

2.4.1 | Speech-in-speech perception

Speech-in-speech-perception was assessed using a version of the Coordinate Response Measure task (Bolia et al., 2000), adapted in-house for Dutch children. The task was programmed and presented with Psychtoolbox-3 in MATLAB 9.1.0 (Mathworks). An HP ProBook 640 G2 laptop, with a 1920 × 1080 screen and Core i5-6200 micro-processor was used to present the task. The auditory stimuli were presented over headphones (Sony Professional MDR-7510) at 70–72 dB SPL, as measured using a RION NA-27 Sound Level Meter with an NH-20 microphone.

Stimuli

Auditory stimuli were of a male and a female voice simultaneously uttering the same sentence frame, where the variable elements were colour and number words: 'Show the dog where the [colour] [number] is' (Dutch: 'Wijs de hond aan waar de [kleur] [nummer] is'). The two sentences always contained different monosyllabic colours (black, blue, green, red, white, or yellow; Dutch: zwart, blauw, groen, rood, wit, geel) and numbers (1, 2, 3, 4, 5, 6, or 8; Dutch: één, twee, drie, vier, vijf, zes, acht). The sentences were spoken by two native Dutch talkers. The stimuli were recorded at a sampling rate of 44.1 Hz separately for each talker in a soundbooth. A customised MATLAB script (MathWorks) was used to align and overlap the female and the male spoken sentences to ensure simultaneous sentence onset time.

Task

Two conditions of 25 trials each were included. In one condition, the participants had to selectively attend to the male voice and to the female voice in the other. After the sentences were presented, children saw a grid of coloured numbers that included every possible colour and number combination. They were asked to click on the colour/number combination spoken by the attended talker. To facilitate children's understanding of task instructions, they were told to help a dog to learn colours and numbers by pointing to the coloured numbers spoken by either a female or a male teacher. To remind the children of the voice they were meant to pay attention to, the cartoon characters of a dog and male teacher (in the attend-male condition) or a dog and female teacher (in the attend-female condition) were displayed on top of the response grid. The proportion of correct trials, averaged across both conditions, was used as the measure of performance accuracy.

2.4.2 | Reading and reading-related skills

Reading tests

Participants were administered the One-Minute-Test (EMT; Brus & Voeten, 1973) and the reading task from the 3DM battery (Dyslexia Differential Diagnosis; Blomert & Vaessen, 2009). The One-Minute-Test includes 116 words (both low- and high-frequency words) that vary from one to four syllables, and are presented in four columns of 29 words each. The score is calculated as the number of words read correctly within one minute. The 3DM reading task includes three subtasks: one with high-frequency words, one with low-frequency words and one with pseudowords. The child is instructed to read correctly as many (pseudo)words as possible within the time limit (30 s per level). The words of each level increase in the number of syllables and syllabic complexity.

Rapid automatized naming (RAN; 3DM battery subtest; Blomert & Vaessen, 2009)

The rapid naming task of the 3DM battery consists of two subtasks: letter and digit naming (Blomert & Vaessen, 2009). In each subtask, 15 items are presented on the screen (five letters or digits repeated three times). Each set of 15 items is presented twice on the screen, with the



items presented in a different order. The participant is instructed to name the items as quickly and accurately as possible. Performance is measured as response time obtained by averaging the response time of the two screen presentations.

Phonological awareness (phoneme deletion; 3DM battery subtest; Blomert & Vaessen, 2009)

The phoneme deletion task contains 23 pseudowords (Consonant-Vowel-Consonant [CVC] or CCVCC structure) presented orally. Participants are asked to leave out the first consonant, the last consonant, or a consonant within a consonant cluster, and to pronounce the remaining pseudoword (e.g., /'dauk/—/d/, what is left?). Here, we report only the accuracy scores, as RTs are not generated if accuracy is below 21.8% (i.e., <5 correct pseudowords); this was the case for 17 of 51 children with dyslexia.

2.5 | Statistical analyses

Statistical analyses were performed using the Statistics and Machine Learning Toolbox in MATLAB (Mathworks) and SPSS (version 26.0, IBM Corp., Armonk, NY). First, we investigated the effects of attentive listening on neural entrainment to rhythmic sound, by comparing ITPC at 3 Hz (the within-band presentation rate) in active and passive conditions on a channel-by-channel basis. Here, we used a Repeated Measures ANOVA, with channel ($n = 63$), condition (active vs. passive) and channel-by-condition interaction as within-subjects factors. Second, to investigate potential effects of dyslexia diagnosis and age differences, group (dyslexic vs. typical readers) and age (mean-centred; Schneider et al., 2015) were also entered respectively as between-subject factor and covariate, in addition to channel, condition and channel-by-condition interaction as within-subjects factors. Greenhouse-Geisser correction was used, as the assumption of sphericity was violated (indicated by Mauchly's sphericity test). Prior to analysis, ITPC values were log-transformed to normalise the underlying distribution. Using the same method, in follow-up analyses, we tested whether the attentional effects were specific to the task-relevant frequency (3 Hz) by comparing also ITPC at 6 Hz (the dual-band presentation or the overall sound presentation rate) in active and passive conditions.

Similarly, we first investigated potential effects of attentive listening on alpha power (8–12 Hz) and total power at relevant frequencies (3 and 6 Hz) by comparing total power in active and passive conditions in repeated measures ANOVAs (separate analyses run for 3 Hz, 6 Hz and 8–12 Hz). Channel ($n = 63$), condition (active vs. passive), and channel-by-condition interaction were included as within-subjects factors. Second, group (dyslexic vs. typical readers) and age (mean-centred; Schneider et al., 2015) were also entered respectively as between-subject factor and covariate. Greenhouse-Geisser correction was used, as the assumption of sphericity was violated (indicated by Mauchly's sphericity test).

To control for potential effects of total power on the differences in ITPC between active and passive listening conditions, we carried out

two additional repeated measures analyses of covariance (ANCOVAs) on ITPC values at 3 Hz and at 6 Hz, with condition (active vs. passive) as within-subjects factor and global power difference (active-passive) at 3 or 6 Hz as covariate at each channel.

We then investigated whether the differences in ITPC between conditions (active-passive) at 3 and 6 Hz and in alpha power were related to behaviourally measured sustained auditory selective attention abilities. To accomplish this, we carried out Spearman rank-order correlations to relate sustained auditory selective attention task performance (d-prime) to ITPC differences (active-passive) at 3 and 6 Hz at each channel. Alpha power was first collapsed across channels (given that no significant channel by conditions was found, see Results section) and then correlated with sustained auditory selective attention task performance. Similarly, we explored the relationship between behavioural sustained auditory selective attention performance and neural metrics (ITPC difference at 3 and 6 Hz and alpha power) versus age (in months) and reading fluency scores (3DM reading task).

To test whether children with dyslexia differed from typical readers in sustained auditory selective attention ability, we compared the two groups' task performance and ITPC and total power differences (active-passive) at 3 and 6 Hz. Because ITPC and total power differences were not normally distributed, we used Wilcoxon rank-sum tests.

Finally, we used a hierarchical linear regression model to ask first whether a diagnosis of dyslexia predicted speech-in-speech perception difficulties. Second, we examined whether these difficulties were modulated by sustained selective attention (behavioural performance and ITPC difference at 3 and 6 Hz). Therefore, in a first step, age and diagnosis were entered in the model. In a second step, sustained auditory selective attention performance or per-channel ITPC difference at 3 or 6 Hz were also entered as regressors. The assumptions of linearity, independence of errors, homoscedasticity and normality of residuals were met for each of the regression models. Data were inspected for outliers that were identified based on standardized residuals, and data points with residual values below -3 and above 3 were excluded from analyses (Osborne & Overbay, 2004).

All channel-based analyses were corrected for multiple comparisons using the False Discovery Rate procedure (FDR; Benjamini & Hochberg, 1995).

3 | RESULTS

3.1 | Sustained auditory selective attention behavioural performance

Mean d-prime for the task was above chance, but with considerable variability across individuals (d-prime = 0.916, SD = 0.725; hit rate: M = 0.358, SD = 0.159; false-alarm rate: M = 0.116, SD = 0.077;). In the following analyses, d-prime (Stanislaw & Todorv, 1999) was taken as a comprehensive measure of behavioural performance. D-prime values were computed from 50 targets and 250 non-targets across the 10 blocks in each active condition.

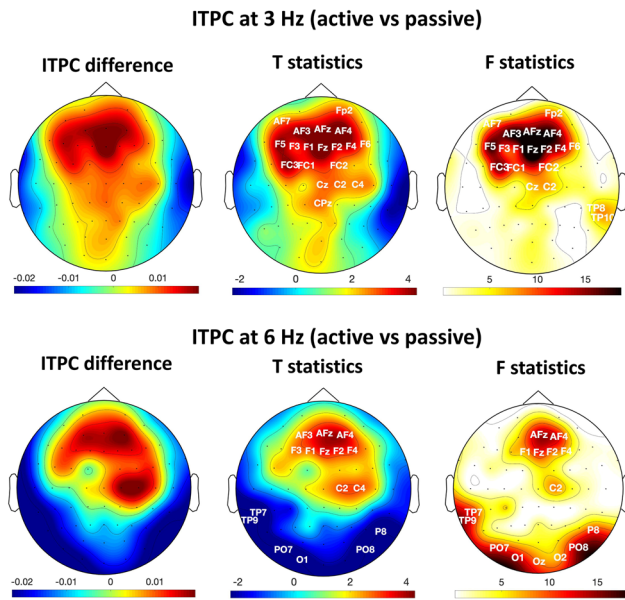


FIGURE 2 ITPC difference between active and passive conditions at 3 and 6 Hz, T-statistics of the pairwise comparisons between ITPC in active versus passive conditions at 3 and 6 Hz and F-statistics of the pairwise comparisons between ITPC in active versus passive conditions, when controlling for total power differences (active-passive) at 3 and 6 Hz. Labelled channels are those showing FDR-corrected significant differences across active and passive conditions.

3.2 | Neural effects of sustained auditory selective attention in children

All models in this section control for age and diagnostic group; for clarity, specific age and group effects are reported in Section 3.4.

Greater fronto-central ITPC at 3 Hz during selective listening: ITPC at 3 Hz differed significantly across channels ($F(10.859, 933.853) = 21.603$; $p < 0.001$, $\eta^2 = 0.201$), and between conditions ($F(1,86) = 12.935$; $p = 0.001$, $\eta^2 = .131$). There was also a significant condition by channel interaction ($F(13.153, 1131.125) = 4.063$; $p < 0.001$, $\eta^2 = .045$). Subsequent FDR-corrected pairwise comparisons showed that ITPC at 3 Hz was higher in active conditions compared to passive listening at fronto-central sites. ITPC differences between active and passive conditions at 3 Hz and T-statistics for FDR-corrected pairwise comparisons are displayed in the topographic plots in Figure 2 (top).

No significant interactions were found with group (channel by group: $F(10.859, 933.853) = .869$; $p = 0.569$, $\eta^2 = .010$; condition by group: $F(1,86) = .846$; $p = 0.360$, $\eta^2 = .010$; channel by condition by group: $F(13.153, 1131.125) = 1.081$; $p = 0.371$, $\eta^2 = .012$) or age (channel by age: $F(10.859, 933.853) = .865$; $p = 0.573$, $\eta^2 = .010$; condition by age: $F(1,86) = .124$; $p = 0.725$; $\eta^2 = .001$; channel by condition by age: $F(13.153, 1131.125) = .655$; $p = 0.810$, $\eta^2 = .008$).

Greater fronto-central but lower posterior 6 Hz ITPC during selective listening: ITPC at 6 Hz differed significantly across channels ($F(6.418, 551.910) = 62.519$; $p < 0.001$, $\eta^2 = .421$) but not between active and passive conditions ($F(1,86) = 3.571$; $p = 0.062$, $\eta^2 = 0.040$). As with 3 Hz ITPC, a significant condition by channel interaction was found ($F(14.825, 1274.927) = 4.662$; $p < 0.001$, $\eta^2 = .051$). FDR-corrected pairwise t-tests comparing active and passive conditions showed that ITPC at 6 Hz was higher at fronto-central sites in the active conditions, but was lower at some temporo-parieto-occipital sites (Figure 2, bottom).

Similarly to ITPC at 3 Hz, no significant interactions were found with group (channel by group: $F(6.418, 551.910) = .944$, $p = 0.467$, $\eta^2 = .011$; condition by group: $F(1,86) = .009$; $p = 0.924$, $\eta^2 = 0.000$; channel by condition by group: $F(14.825, 1274.927) = 1.118$; $p = 0.335$, $\eta^2 = .013$) or age (channel by age: $F(6.418, 551.910) = 1.994$; $p = 0.060$, $\eta^2 = .023$; condition by age: $F(1,86) = .100$; $p = 0.753$; $\eta^2 = .001$; channel by condition by age: $F(14.825, 1274.927) = .533$; $p = 0.922$, $\eta^2 = 0.006$).

No effect of auditory attention on total power at 3 Hz: Total power at 3 Hz differed significantly across channels ($F(1.674, 143.996) = 19.212$; $p < 0.001$, $\eta^2 = 0.183$), with no significant effect of condition across all electrodes ($F(1,86) = 0.648$; $p = 0.423$, $\eta^2 = .007$) or significant condition by channel interaction ($F(1.442, 124.001) = 1.864$; $p = 0.170$, $\eta^2 = .021$). No significant interactions were found with group (channel by group: $F(1.674, 143.996) = 1.595$, $p = 0.209$, $\eta^2 = .018$; condition by group: $F(1,86) = 1.629$; $p = 0.205$, $\eta^2 = .019$; channel by condition by group: $F(1.442, 124.001) = 1.250$, $p = 0.281$, $\eta^2 = .014$) or age (channel by age: $F(1.674, 143.996) = 1.251$; $p = 0.285$, $\eta^2 = .014$; condition by age: $F(1,86) = 3.512$; $p = 0.064$; $\eta^2 = .039$; channel by condition by age: $F(1.442, 124.001) = 868$; $p = 0.391$, $\eta^2 = 0.010$).

Total power in the active and passive conditions, and the between-condition difference in power are displayed in the topographic plots in Figure 3.

No effect of auditory attention on total power at 6 Hz: Total power at 6 Hz differed significantly across channels ($F(2.945, 253.276) = 99.391$; $p < 0.001$, $\eta^2 = 0.536$), with no significant effect of condition across all electrodes ($F(1,86) = .302$; $p = 0.584$, $\eta^2 = .003$) or significant condition by channel interaction ($F(3.915, 336.732) = 1.199$; $p = 0.474$, $\eta^2 = .010$). No significant interactions were found with group (channel by group: $F(2.945, 253.276) = .685$, $p = 0.560$, $\eta^2 = .008$; condition by group: $F(1,86) = .358$; $p = 0.551$, $\eta^2 = .004$; channel by condition by group: $F(3.915, 336.732) = 1.199$, $p = 0.311$, $\eta^2 = .014$). We found a significant channel by age interaction ($F(2.945, 253.276) = 4.350$; $p = 0.005$, $\eta^2 = .0048$); however, this is of exceedingly small effect size and unrelated to attention, so we do not consider it further. The other interactions with age were found non-significant (condition by age: $F(1,86) = 1.354$; $p = 0.248$; $\eta^2 = .003$; channel by condition by age: $F(3.915, 336.732) = .940$; $p = 0.439$, $\eta^2 = 0.011$).

To ask whether potential power differences between active and passive conditions might account for ITPC condition effects, we repeated the channel-wise ANCOVAs on ITPC at 3 and 6 Hz, but included as

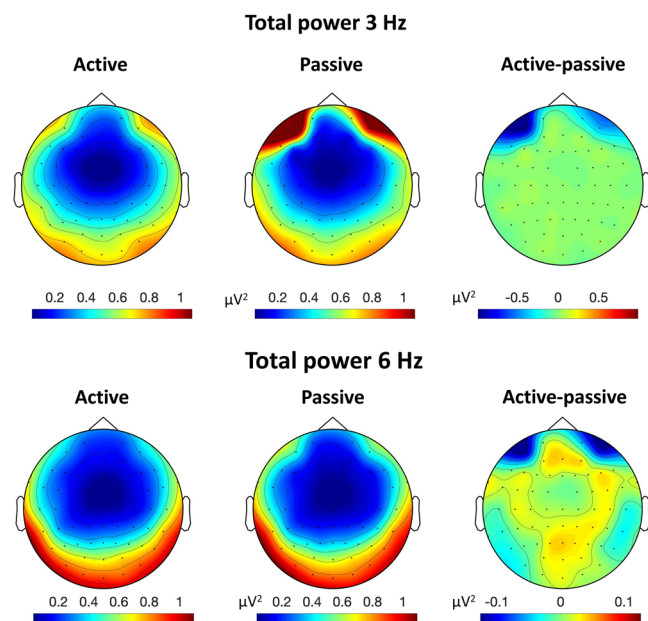


FIGURE 3 Total power during active conditions, passive condition and the difference between active and passive conditions across channels at 3 Hz (top) and 6 Hz (bottom). There were no significant power differences between attention conditions.

covariate the total active-passive difference in power at the same rate (3 Hz or 6 Hz).

As can be seen by comparing the topographic plots showing T-statistics (total power not included in model) and F-statistics (total power included) in Figure 2, results were mostly unchanged when controlling for total power differences. As previously, ITPC at 3 Hz was higher in active conditions compared to passive listening at fronto-central sites, although in two central channels (C4, CPz), this difference dropped below significance levels. We also observed greater power for passive versus active conditions at two temporo-parietal sites (TP8, TP10). When controlling for total power difference at 6 Hz, ITPC at 6 Hz was again higher at fronto-temporal sites, but 3 channels (C4, AF3, F3) dropped below significance; conversely, we observed Passive > Active 6 Hz ITPC in additional two posterior channels (Oz, O2).

Total alpha (8–12 Hz) power is suppressed during selective listening: Alpha power differed significantly across channels ($F(8,186, 720.344) = 351.968$; $p < 0.001$, $\eta^2 = 0.800$) and conditions ($F(1,88) = 4.604$; $p = 0.035$, $\eta^2 = .050$; Figure 4). There was no significant condition by channel interaction ($F(4.855, 427.282) = 1.233$; $p = 0.293$, $\eta^2 = .014$), thus in the following analyses alpha power was collapsed across channels.

Controlling for age and diagnostic group, alpha power differed across conditions, with an overall increase in alpha power suppression for the active conditions versus passive listening ($F(1,86) = 8.527$; $p = 0.004$; $\eta^2 = .090$). There were no significant condition by diagnosis ($F(1,86) = 2.339$; $p = 0.130$, $\eta^2 = .026$) or condition by age ($F(1,86) = .113$; $p = 0.737$, $\eta^2 = .001$) interactions.

3.2.1 | Sustained auditory selective attention performance is positively related to ITPC (active-passive) at 3 Hz but not 6 Hz or alpha power suppression

The active-passive condition difference in ITPC at the attended band rate (3 Hz) was significantly correlated with sustained auditory selective attention task performance across multiple fronto-central sites (FDR-corrected $p < 0.05$; Figure 5). In contrast, the ITPC difference (active-passive) at 6 Hz was *not* correlated with task performance at any electrode. Alpha power difference (active-passive) across channels was not correlated with sustained auditory selective attention task performance ($p > 0.05$).

3.2.2 | Attentional behavioural performance improves with age, but age is not related to ITPC (active-passive) at 3 Hz or 6 Hz; overall alpha power is negatively correlated with age

We found a significant correlation between sustained auditory selective attention performance and age (in months), with performance improving between 7 and 12 years of age ($\rho = 0.235$, $p = 0.027$; Figure 6).

Turning to EEG data, channel-wise Spearman correlations between age and ITPC difference (active-passive) showed no significant relationships, either at 3 Hz or 6 Hz ($p > 0.05$, FDR-corrected). Alpha power difference (active-passive) across channels was not correlated with age ($\rho = 0.140$, $p = 0.189$). However, we found that alpha power in both active ($\rho = -0.242$, $p = 0.022$) and passive listening ($\rho = -0.211$, $p = 0.048$) conditions was negatively correlated with age.

3.2.3 | Children with and without dyslexia do not differ in behavioural or neural metrics of sustained auditory selective attention

Children with and without dyslexia did not perform significantly differently in the sustained auditory selective attention task (dyslexic readers: $M = 0.82$, $SD = 0.59$; typical readers: $M = 1.04$, $SD = 0.86$; $Z = -0.979$, $p = 0.328$; Figure 7).

Similarly, no significant differences between children with and without dyslexia were observed for active-passive ITPC differences at 3 or 6 Hz ($p > 0.05$, FDR-corrected; frequentist and Bayesian statistics in Supplementary Material). This was somewhat unexpected given the patterns seen in the topographic plots (Figure 8), which were suggestive of potential between-group differences in active-passive ITPC, particularly at the 3 Hz rate. However, as shown in Supplementary Material (Figure S1) there was substantial within-group variability in the distribution of ITPC values (active-passive) at 3 Hz.

As with ITPC, no significant differences between children with and without dyslexia were observed for active-passive total power differences at 3 or 6 Hz ($p > 0.05$, FDR-corrected; Figure 9). When

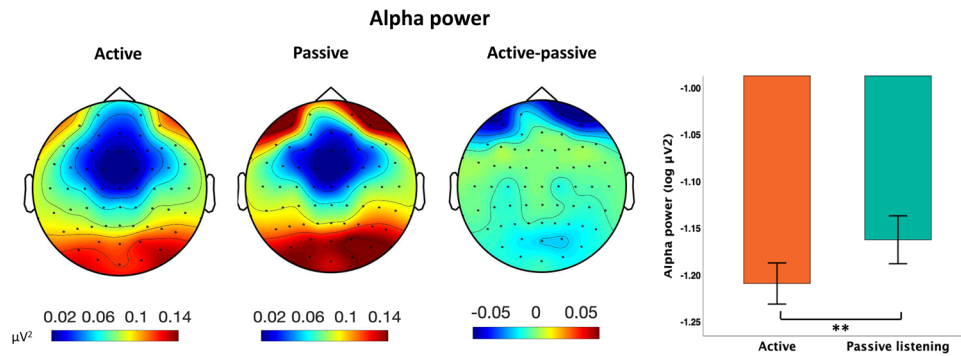


FIGURE 4 Left topoplots show total alpha power during active conditions, the passive condition and the difference between active and passive conditions. The right bar graph shows the significant difference in alpha power between attention conditions, collapsed across channels, with increased alpha power suppression in the active listening conditions compared to passive listening.

Selective attention versus ITPC difference at 3 Hz

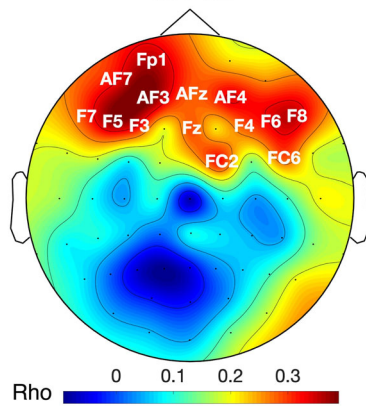


FIGURE 5 Topographic plot displaying the rho values of the Spearman correlations between sustained selective attention performance (d-prime) and ITPC difference between active and passive conditions at 3 Hz. The labelled channels are those with FDR-corrected $p < 0.05$.

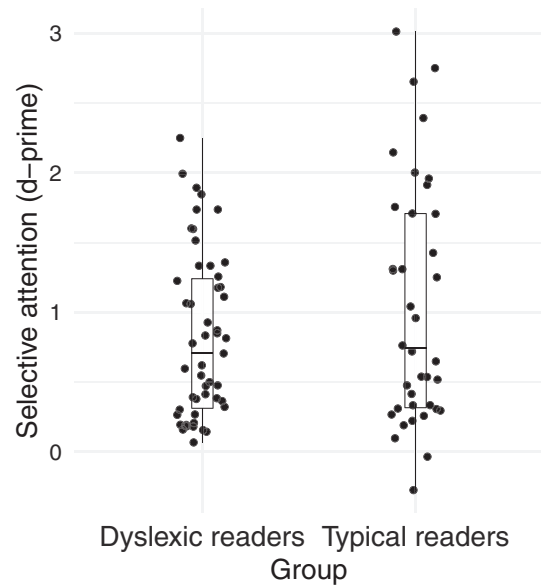


FIGURE 7 Sustained auditory selective attention task performance of children with and without dyslexia did not differ significantly.

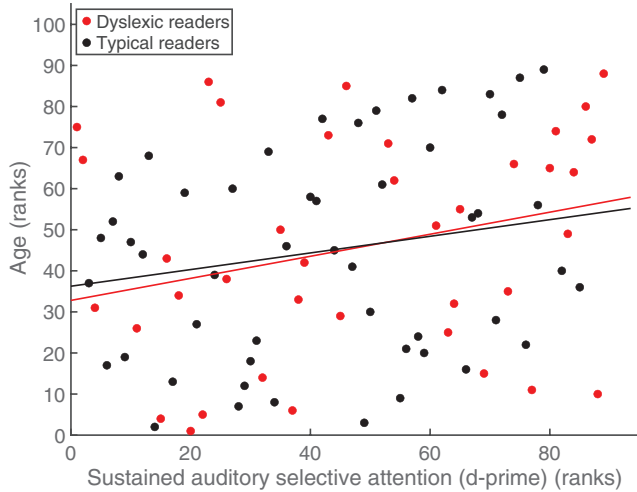


FIGURE 6 Sustained auditory selective attention (d-prime) was significantly correlated with children's age.

controlling for total power differences (active-passive) at relevant frequencies, results of the group comparison between children with and without dyslexia did not change: no significant differences were observed for active-passive ITPC differences (active-passive) at 3 or 6 Hz ($p > 0.05$, FDR-corrected). Finally, no significant differences between children with and without dyslexia were observed for active-passive alpha power (across channels; $Z = 0.975$, $p = 0.298$).

3.2.4 | Attentional performance but not neural metrics is positively related to reading fluency and phonological awareness abilities

Sustained auditory selective attention performance and reading fluency (as assessed by the '3DM reading subtest') were positively correlated ($\rho = 0.288$, $p = 0.006$), and remained correlated after

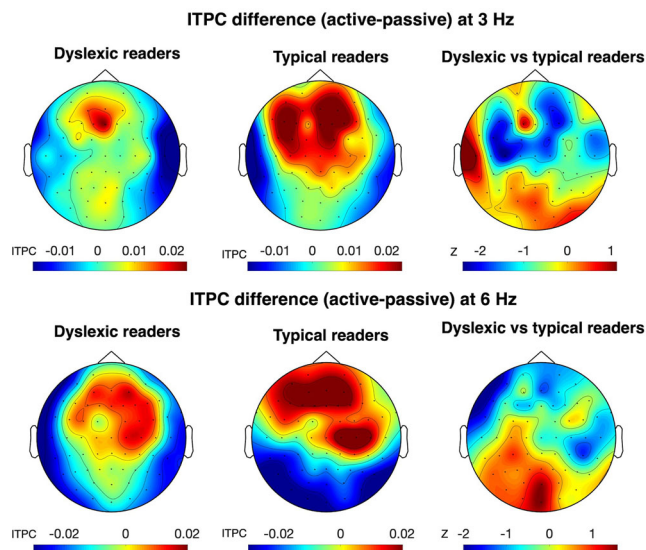


FIGURE 8 ITPC differences (active-passive) at 3 Hz and at 6 Hz for the group of children with and without dyslexia and the z values of the pairwise comparisons. No significant group differences were found at any channels after FDR-correction was applied.

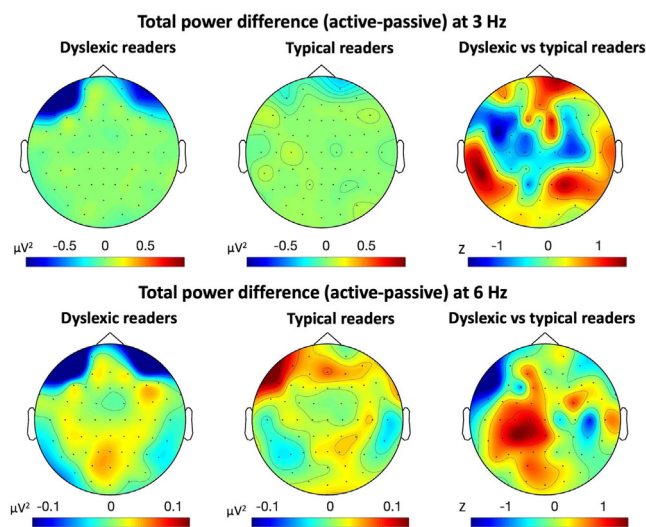


FIGURE 9 Total power differences (active-passive) at 3 Hz (top) and at 6 Hz (bottom) for the group of children with and without dyslexia and the z values of the pairwise comparisons. No significant group differences were found at any channels after FDR-correction was applied.

both variables were age-detrended ($\rho = 0.236, p = 0.026$). When the same correlational analyses were run separately for each group, we found that once the effect of age was removed, reading fluency abilities were correlated with sustained auditory selective attention only in dyslexic readers ($\rho = 0.322, p = 0.022$), but not in typical readers ($\rho = 0.089, p = 0.593$; Figure 10a). Using Fisher's r-to-z transformation for non-parametric correlations (Sheshkin, 2004), we found that these correlations were not different ($p = 0.285$).

Sustained auditory selective attention and phonological awareness (as assessed by the '3DM phonological deletion subtest') were positively correlated ($\rho = 0.404, p = 0.0001$), even when both variables were age-detrended ($\rho = 0.337, p = 0.002$). Group-wise correlational analyses showed that once the effect of age was removed, phonological awareness abilities were significantly correlated with sustained auditory selective attention in typical readers ($\rho = 0.428, p = 0.012$), but not in dyslexic readers ($\rho = 0.226, p = 0.114$; Figure 9b). Fisher's r-to-z transformation indicated that these correlations were not different ($p = 0.339$). Turning to EEG, channel-wise Spearman correlations revealed no significant relationship between reading fluency or phonological awareness and ITPC difference (active-passive) at 3 Hz or 6 Hz ($p > 0.05$, FDR-corrected).

3.2.5 | Speech-in-speech perception is impaired in children with dyslexia and modulated by non-speech sustained auditory selective attention performance

Two participants were excluded from the analyses due to extremely poor performance in one of the two conditions of the speech-in-speech perception task (accuracy $\leq 4\%$).

On average, dyslexic readers reported correctly 68.5% (SD = 14.9) and typical readers 74.4% (SD = 11.3%) of targets (colour-number combinations). Reports of targets embedded in the distracting voice occurred very rarely. In fact, across conditions (attend-female and attend-male voice), 71% of dyslexic readers (35 out of 49) and 66% of typical readers (25 out of 38) reported the target embedded in the distracting voice in 2 or less trials (out of 50). Therefore, only the proportion of correctly reported targets (averaged across conditions) was taken as a measure of performance in the following analysis.

A participant with dyslexia was removed from the regression model for having standardised residuals below 3.0. In the remaining participants ($N = 86$), age ($\beta = 0.437, p < 0.001, 95\% \text{ CI} = 0.002-0.006$) and diagnosis ($\beta = -0.200, p = 0.041, 95\% \text{ CI} = -0.100 \text{ to } -0.002$) significantly predicted speech-in-speech perception abilities (overall regression model: $R^2 = 0.229, F(2,83) = 12.337, p < 0.001$), with older children and children without dyslexia (Figure 11a) showing better speech-in-speech perception skills. Adding sustained auditory selective attention performance revealed that speech-in-speech perception abilities were associated with sustained auditory selective attention performance ($\beta = 0.248, p = 0.013; \text{CI} = 0.009-0.77$; Figure 11b). In this model, age remained a significant predictor ($\beta = 0.371, p < 0.001; \text{CI} = 0.002-0.005$), but diagnosis did not ($\beta = -0.168, p = 0.079; \text{CI} = -0.090 \text{ to } 0.005$; R^2 change = .056, $F(1,82)$ change = 6.469; $p = 0.013$; overall regression model: $R^2 = 0.286, F(3,82) = 10.923, p < 0.001$).

In contrast, adding to the model ITPC difference at 3 Hz or at 6 Hz on a channel by channel basis did not explain additional significant variance ($p > 0.05$, FDR-corrected). In the models, the statistical significance and the predictive value of age and group remained unchanged.

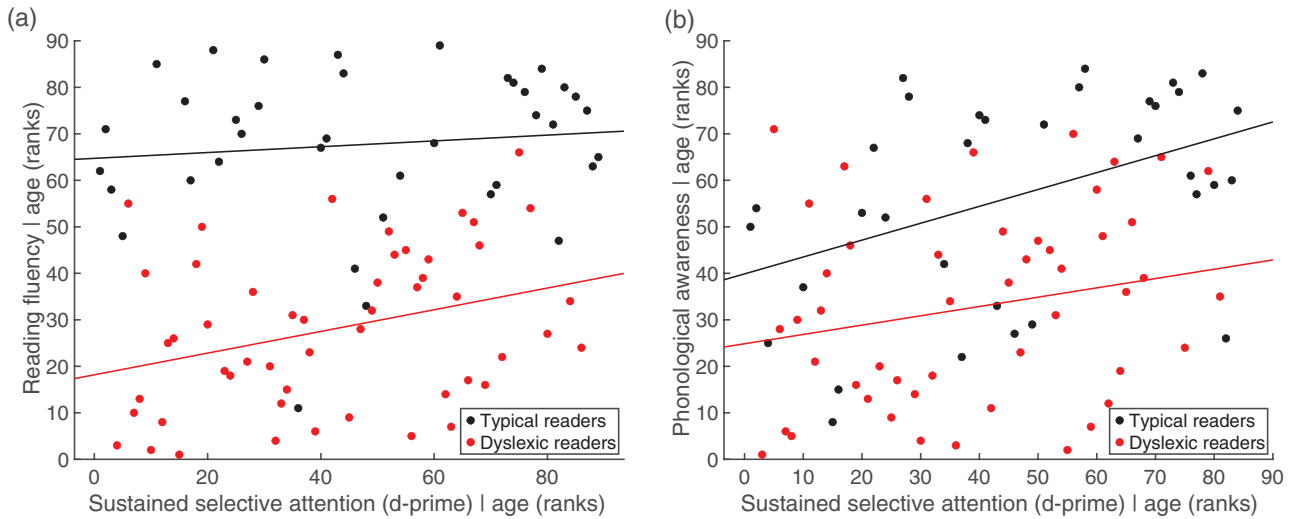


FIGURE 10 (a) Sustained selective attention (d-prime) was significantly correlated with reading fluency abilities in dyslexic readers (in red) but not in typical readers (in black), once the effect of age was removed from both variables. (b) Conversely, sustained auditory selective attention was significantly correlated with phonological awareness in typical readers (in black) but not significantly in dyslexic readers (in red), once the effect of age was removed from both variables. (Note that correlation values did not significantly differ significantly across the two groups).

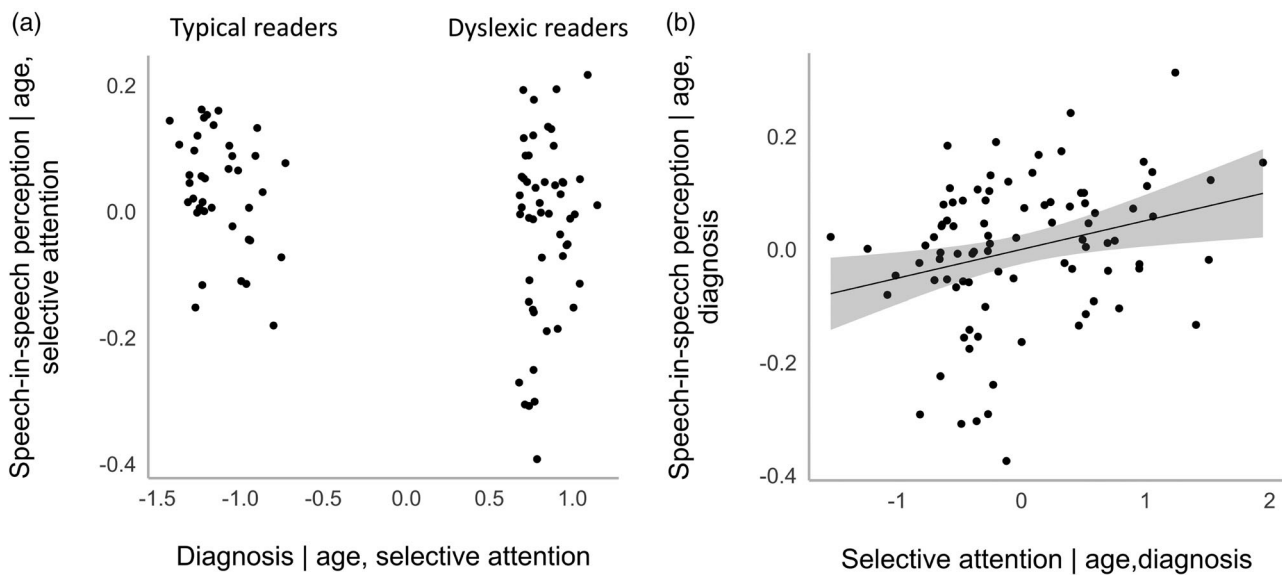


FIGURE 11 (a) Children with dyslexia performed worse in the speech-in-speech perception task, once the effect of age and sustained selective attention (with a non-significant trend) were partialled out. (b) The behavioural measure of sustained selective attention predicted speech-in-speech perception abilities, once the variance explained by age and diagnosis were partialled out. The grey shaded area represents the 95% confidence interval.

4 | SUMMARY AND DISCUSSION

In the present EEG study, we investigated the neural (EEG) correlates of non-speech sustained auditory selective attention in 7-to-12-year-old children. We examined whether behavioural and neural correlates of sustained auditory selective attention differ between children with and without dyslexia, and/or explain individual variability in children's reading fluency and speech-in-speech perception abilities.

Sustained auditory selective attention towards the target stream increased phase alignment—but not total power—at the attended-stream 3 Hz rate. Both dyslexic and typically reading children show strong stimulus- and attention-related phase alignment at the attended-stream frequency, with only the attention-related phase alignment positively related to sustained auditory selective attention performance. Children with and without dyslexia did not differ significantly in the degree of neural phase alignment or in the strength of



the oscillation at the attended stream, nor did their overall behavioural performance differ. However, sustained auditory selective attention performance and reading fluency were moderately correlated; this relationship held when age was factored out. Sustained auditory selective attention performance was also associated with phonological awareness abilities and speech-in-speech performance. By contrast, the degree of stimulus- or attentionally-related neural phase alignment was not significantly associated with either reading fluency, phonological awareness or speech-in-speech perception.

4.1 | Neural correlates of non-speech sustained auditory selective attention

We assessed non-speech sustained auditory selective attention by presenting children with two three-tone isochronous streams in two frequency bands. Children attended to one of the two streams, ignored the other stream, and detected occasional three-tone sequence repeats within the target stream. We compared the two conditions where children selectively directed their attention to one of the two streams versus a passive condition where children passively listened to the streams without performing any task. The temporally interleaved streams were both presented at 3 Hz, and thus the overall sound presentation rate was 6 Hz. Based on previous findings from our lab with young adults (Laffere, Dick, & Tierney, 2020) and older children (Laffere, Dick, Holt, et al., 2020), we predicted that sustained auditory selective attention to either stream would be associated with an increase in inter-trial phase coherence at the attended frequency (3 Hz) but not at the cross-band frequency (6 Hz).

We found that inter-trial-phase-coherence at the attended band (3 Hz) increased in frontal areas of the scalp when children were directing their attention to one of the two streams. This finding aligns with previous EEG and electrocorticography (ECoG) reports with human and non-human participants showing increased phase alignment at the attended frequency (Besle et al., 2011; Laffere, Dick, Holt, et al., 2020; Laffere, Dick, & Tierney, 2020; Lakatos et al. 2013). There was a relative spatial dissociation between electrode sites showing the greatest phase consistency in passive listening versus sites showing increased attention-linked phase tracking. These topographic differences may suggest that our findings reflect more than attentional enhancement of sensory-driven neural responses (Choi et al., 2014; Dai et al., 2018; Hillyard et al., 1973). In fact, they are potentially more congruent with the notion that neural alignment with the temporal structure of external stimuli resulted from attention-driven modulation of endogenous oscillatory activity (Ding & Simon, 2012; Zion Golumbic et al., 2013; see for a discussion: Haegens et al., 2018; Zoefel, Ten Over, & Sack, 2018). Here, the low spatial resolution of the EEG data does not allow for a conclusive interpretation of potential localization differences between passive listening and sustained auditory selective attention conditions. Future studies employing high spatial-resolution techniques will be needed to clarify the neural bases underlying these topographic differences.

Contrary to our expectations based on previous studies (Laffere, Dick, Holt, et al., 2020; Laffere, Dick, & Tierney, 2020), we also found differences between active and passive conditions at the cross-band frequency rate (6 Hz). Here we observed generally *decreased* phase consistency in the active conditions in posterior regions of the scalp. A less-pronounced effect with reversed polarity was also found in some fronto-central channels. The decreased phase consistency at posterior electrodes at the sound presentation rate could suggest a mechanism of suppressed representation of the cross-band stimuli favouring the selection and integration of the task-relevant sound stream. However, the fact that the relationship between task performance and phase consistency was only found at the attended frequency (3 Hz) does not further support the relevance of this mechanism to successful task performance. By comparison, the relationship between task performance and increased phase alignment at the attention-modulated rate suggests that this measure of neural coupling might serve as an electrophysiological index of children's ability to direct focus, sustain it over time, and integrate information within the attended stimuli.

We have also examined total power at the stimulus- and attentionally-related frequency to verify that potential differences between conditions in overall neural activity strength or signal to noise ratio at these frequencies did not confound the attentional effects on phase alignment across trials. Sustained auditory selective attention to the target stream did not modulate total power at the attended- or stimulus-rate. Furthermore, the effect of sustained selective attention on phase alignment—i.e., increased phase alignment at the attended frequency—remained when power differences at relevant frequencies were partialled out. These findings further support the hypothesis that sustained auditory selective attention modulates the timing of neural activity at the task-relevant frequency, and show that sustained auditory selective attention did not lead to an overall increase in oscillatory activity at the same frequency. Finally, as one would expect given previous findings in the literature with visual paradigms (e.g., Sokoliuk et al., 2019) we found that EEG alpha (8–12 Hz) power decreased when participants were engaged in sustained auditory selective attention, compared to passive listening.

4.2 | Comparison of children with and without dyslexia: non-speech sustained auditory selective attention and its relation to speech-in-speech perception, reading fluency and phonological awareness

In recent years, researchers have emphasised the heterogeneity of domain-general and language-specific symptoms in developmental dyslexia, supporting a multiple deficits view of neurodevelopmental disorders (Astle & Fletcher-Watson, 2020; Pennington, 2006; Peterson & Pennington, 2015). Among these candidate deficits, there are difficulties with visual and auditory non-speech attention (e.g., Gabay et al., 2020; Ruffino et al., 2014) and speech perception in complex acoustic settings (e.g., Calcutt et al., 2018), which have been reported



to be more common in children with dyslexia. Evidence regarding non-speech selective attention abilities and their neural mechanisms in children with dyslexia is limited. Here, and contra our initial hypotheses, we did not find that children with dyslexia performed significantly worse than typical readers on the sustained auditory selective attention task. Similarly, no group differences were found in attentional modulation of phase alignment across trials or of total power, either at the frequency of the attended band (3 Hz) or at the overall sound presentation frequency (6 Hz).

Although this suggests the absence of clear-cut deficits in non-speech sustained selective attention, we cannot draw strong conclusions about this null effect. Indeed, there was a trend at some fronto-central electrodes for dyslexic readers to show lower attentional modulation of phase alignment compared to typical readers, although we hasten to add that this is also not evidence for a group difference. This issue might be clarified by modulating task difficulty, as the current paradigm was quite challenging for children in this age range. The poor performance in a subset of children may have obscured group differences that would have emerged by employing tasks with a lower level of difficulty (relevant issues are discussed in Church et al., 2010; Laurie-Rose et al., 2005).

To ensure that putative group differences in the neural index of sustained auditory selective attention were not confounded by differences in non-selective, exogenous entrainment to rhythmic sound at low frequencies (as predicted by the temporal sampling theory, Goswami, 2011), we also compared phase coherence at 3 and 6 Hz in each condition (in Supplementary Material). These analyses revealed no significant group differences. Previously, group differences in neural entrainment were found more consistently found in the delta band (~2 Hz, the rate of stressed syllable production) using non-speech (Hämäläinen et al., 2012; Molinaro et al., 2016) and speech (Molinaro et al., 2016; Power et al., 2013) stimuli. Our findings aligned with those of previous studies showing similar auditory entrainment at the theta band (the syllable rate; Hämäläinen et al., 2012; Molinaro et al., 2016; Varghese, Goswami, Burnham & Kalashnikova, 2023; see also for a recent summary and a replication study, Lizarazu et al., 2021) between dyslexic and typical readers.

However, the significant relationship between dyslexic readers' reading fluency and target detection performance in the sustained auditory selective attention task indicates that auditory attention is potentially one of the underlying factors explaining individual differences in reading fluency for children with literacy problems. This observation corroborates and extends previous findings showing that visual attentional skills are associated with the development of reading abilities (e.g., ten Braak et al., 2018; van de Sande et al., 2013) and that visual and auditory attentional skills are linked to pseudoword reading abilities in dyslexia (Facoetti et al., 2006, 2010; Gabay et al., 2020). It may indicate that impaired auditory attention represents a risk for more severe problems with reading fluency, even though auditory attentional problems alone are not sufficient to develop reading deficits, as shown by the lack of an overall group difference. These observations align with a multiple deficits account of dyslexia, proposing that no single deficit is either necessary or sufficient to lead to

reading deficits but rather that several interacting factors contribute to the emergence of reading problems (e.g., Pennington, 2006). Sustained auditory selective attention skills were also related to phonological awareness abilities in whole-group analyses, suggesting the relevance of top-down attentional control for the awareness of the sound structure of the continuous speech signal. This finding also fits with the notion that phonological awareness tasks are goal-directed acoustic tasks that require attention to some speech cues while suppressing other salient features in order to segment and manipulate sound segments (McCandliss & Yoncheva, 2011). In contrast, we did not find a significant relationship between our neural measure of sustained auditory selective attention and reading fluency or phonological awareness. One possible interpretation is that the neural metric is a relatively pure measure of sustained auditory selective attention, while the behavioural measure of attention may also tap into other cognitive functions (e.g., other executive skills such as working memory or motivation), which, together with sustained auditory selective attention, facilitate the development of phonological processing and fluent reading. In particular, the repetition detection task may have required information maintenance, although a 1-back task generally minimises working memory load (compared to other n-back levels; e.g., Pelegrina et al., 2015).

In line with previous studies showing difficulties with speech perception in suboptimal listening conditions in dyslexia (e.g. Bradlow et al., 2003; Calcus et al., 2015, 2017; Ziegler et al., 2009), we found that children with dyslexia performed more poorly in the speech-in-speech perception task. Given the importance of accurate perception of speech cues for phonological development (e.g., Goswami, 2011), we speculate that these difficulties may hamper the establishment of stable phonological representations and/or access to phonological information. Both of these have previously been related to the proposed phonological impairment in dyslexia (Ramus & Szenkovits, 2008; Snowling, 2000). Moreover, children's inter-individual variability in speech-in-speech perception was explained by sustained auditory selective attention task performance, but not by the neural metrics, consistently with a previous in-lab study with older children (Laffere, Dick, Holt, et al., 2020). The differential relationship of speech-in-speech perception with behavioural and neural attentional metrics suggests that other cognitive factors may contribute to successful target identification in the attentional task as well as in the speech-in-speech perception task (e.g., working memory). Alternatively, it is possible that the behavioural attentional measure reflects both the ability to direct focus on the task-relevant stimulus stream and to suppress the task-irrelevant stimulus stream. In contrast, neural metrics may reflect to a greater extent one of the two components (e.g., neural enhancement of the attended stream). Nonetheless, the result provides empirical evidence for the hypothesis that auditory attention is related to speech-in-noise perception difficulties as well as to reading impairments in dyslexia (Calcus et al., 2018; Ziegler et al., 2009).

Future investigations employing multiple speech perception tasks with different maskers will potentially clarify whether the oft-reported intra-individual inconsistency observed across different noise conditions is also driven by differences in auditory attentional skills (Calcus

et al., 2018; Hazan et al., 2009; Messaoud-Galusi et al., 2011) and by the extent to which different noise conditions tap into sustained selective attention. To match task demands, certain task characteristics of the speech-in-speech perception task were kept consistent with the selective sustained attention paradigm, including the presence of two competing signals with embedded targets and the requirement to direct attention to one of the two while suppressing the interference of the competing signal. Nonetheless, there are also considerable differences between the speech and non-speech paradigms. These include (1) the requirement to listen to stereotyped short sentences and report the embedded target via a visual grid of potential targets, versus consistently integrating information across different acoustic dimensions and performing a 1-back task, and (2) the different level of demand on sustained attention, where a speech-in-speech trial was only 2.8 s, but a sustained auditory selective attention block was 40 seconds long. These considerable cross-task differences lessen the possibility that the significant association between the two is solely driven by procedural similarities. Therefore, this finding lends further support to the hypothesis that domain-general skills facilitate speech perception under challenging acoustic environments (Oberfeld & Klöckner-Nowotny, 2016; Strait & Kraus, 2011; Tierney et al., 2020), and extends it to young children with and without dyslexia.

To conclude, the present investigation highlights the importance of examining domain-general processes and their potential contribution to reading and reading-related skills. Further determining the nature, the magnitude, and the extent to which sustained auditory selective attention is involved in reading acquisition impairments has potential for offering new perspectives for the individualisation of intervention programs. Follow-up studies that further disambiguate the attentional components with more or less relevance for reading acquisition may provide valuable tools to assess attention skills during diagnostic assessments for identifying children with subtle attentional difficulties, which may not otherwise emerge with standard diagnostic assessment to identify the possible presence of comorbid ADHD. In turn, these assessments could indicate whether attention training may be beneficial for some children, in addition to standard remediation protocols targeting reading-specific processes, such as phonological and letter-speech sound learning processes. In future studies, testing the relationship between experimental and standardised measures of selective attention in dyslexic readers could potentially clarify the nature of subclinical attentional deficits often reported in dyslexic readers.

Finally, the observation of group-level speech-in-speech perception difficulties in children with dyslexia suggests that they may struggle to follow verbal instructions in complex listening environments. Strategies for noise reduction within classrooms or other educational settings may benefit children with dyslexia, especially those identified as more at risk for speech-in-noise perception difficulties.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sets for which parents have given (anonymised) data sharing consent are available on reasonable request. Data are available from the Ethical Committee Psychology, Faculty of Psychology and Neuroscience, Maastricht University. Contact: Marcel Schrijnemaekers, professional secretary Ethical Committee Psychology of FPN, ercpn-fpn@maastrichtuniversity.nl.

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